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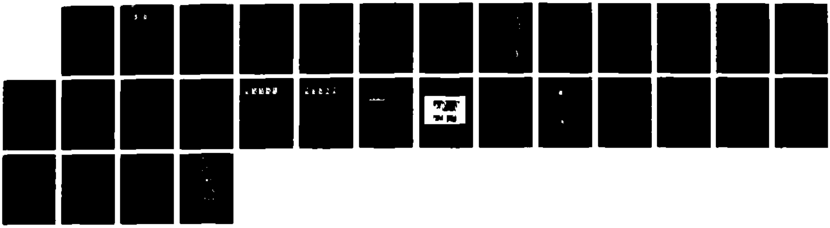

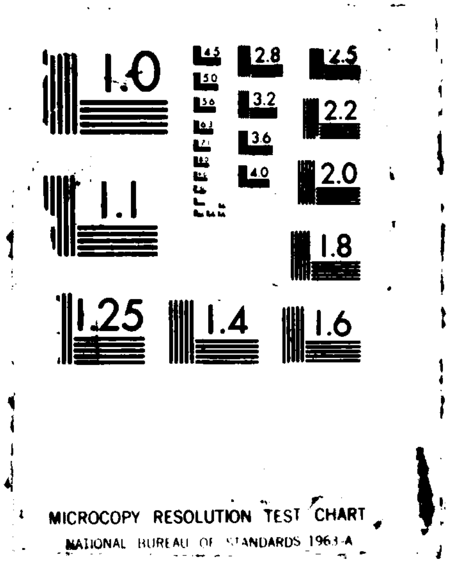
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The recent accomplishments are reviewed for a research program employing combined analytical-experimental techniques to study the three-dimensional characteristics and behavior of vortex motions associated with the turbulence production process in turbulent boundary layers. Progress is described in the development of a new image processing technique which allows the derivation of quantitative data from flow visualization images. The method is used to "search" for the role of hairpin vortices in the turbulence production process. In the analytical portion of the study, calculations have been carried out to compute the evolution of a hairpin vortex in a shear flow; the interaction of a pair of hairpins has been examined as well as the viscous response at a wall due to the motion of a hairpin vortex. Comparison of these computer simulations with the experimental studies is very encouraging. Computations for the evolving flow between wall-layer streaks during a typical cycle in the wall layer of a turbulent boundary layer have also been carried out; these studies show two possible routes to breakdown of the wall-layer flow leading to the production process.

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Annual Technical Report

on the

UNSTEADY BEHAVIOR OF THREE-DIMENSIONAL VORTICES RELEVANT TO TURBULENT BOUNDARY LAYERS

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1. INTRODUCTION

The present report outlines the recent accomplishments of a combined analytical-experimental program which has as its continuing objective the examination, synthesis, and modeling of turbulent boundary layer structure via examination of the three-dimensional characteristics and behavior of vortex motions which are believed to be associated with the production process in turbulent boundary layers. In particular the motions of closed loop vortices and hairpin vortices are examined; the objective is to elucidate how such vortices interact with the viscous flow near a wall and how they interact with one another. At present, we believe that such vortices may be building blocks for the turbulent boundary layer and consequently a proper understanding of the effects of such vortices is essential to the goal of delineating the processes of turbulence production and regeneration near a wall.

The broad objectives of the program, since it was initially funded at Lehigh in 1978, have been to establish fundamental understanding of key vortical flows which appear to develop in proximity to a surface during turbulence production, and to develop techniques to:

1) Simulate and predict the two and three-dimensional characteristics of these vortical flow structures, particularly adjacent to solid boundaries;

2) Improve turbulence prediction models based on the identified behavior of the vortical structures and create the requisite numerical procedures to facilitate the implementation of these models;

3) Establish the effects of geometric modifications on vortical structure, and the resultant effect on surface drag.

4) Improve the experimental detection, analysis, and presentation of three-dimensional, turbulent-type flow behavior.

This progress report is a highlighted review of recent results which bear upon the above objectives. The remainder of the report is configured as follows. Section 2 reviews a recent analytical development of the program; recent experimental work is reviewed in section 3. A final section reviews the recent papers, presentations, and thesis work which have been the product of the ongoing research program.

2. HIGHLIGHTS OF ANALYTICAL PROGRAM

During the past year the analytical program has focussed on three different topics and progress is summarized briefly below.

2.1 Calculation Methods for Unsteady Separation

Unsteady flow separation occurs in a variety of physical situations such as the flows occuring in turbomachinery and over the surface on a pitching airfoil. In the work carried out in previous years under this contract, it has been determined that the bursting phenomena observed in turbulent boundary layers is likely associated with moving hairpin vortices in the outer region of the boundary layer; the moving hairpin vortices induce an unsteady separation in the viscous flow near the wall which ultimately evolves into an eruption of wall-layer fluid. The bursting event can be thought of as a strong viscous-inviscid interaction between the viscous flow in the wall layer and the outer inviscid (but rotational flow). The event is of relatively brief duration but is of fundamental importance since this is the principle mechanism by which new vorticity is introduced into the outer region of the boundary layer. Essentially all Reynolds stress production occurs during this event and consequently it is of interest to develop calculation methods to compute such an event.

In most instances of unsteady separation, the process initiates in a thin viscous layer near the surface in the form of the appearance of a closed recirculating eddy. As the process matures, a rapid thicknening of the viscous flow occurs near the eddy; the process culminates with a strong interaction which often results in the ejection of a secondary eddy from the boundary layer near the surface. In past studies of various separating viscous flows, considerable difficulty is experienced in continuing the numerical integrations of the boundary-layer flow as an interaction is about to take place. The difficulty occurs partially because most methods of this type have been carried out using a fixed numerical mesh in an Eulerian frame of reference; as the viscous flow begins to erupt, it does so in a streamwise band of relatively narrow extent in locations which are not possible to predict a priori. This means that as an eruption begins to evolve it eventually becomes impossible to continue numerical integrations in an Eulerian frame of reference with good accuracy. During the past year a method has been developed to compute the onset of a strong viscous-inviscid interaction in which the flow evolutiion beyond a certain stage is computed using a Lagrangian method. In this scheme, the trajectories of individual fluid particles are tracked as the eruption starts.

The method has been applied to the vortex-boundary-layer problem depicted schematically in figure 1; this is the simplest situation where a moving vortex is known to generate a

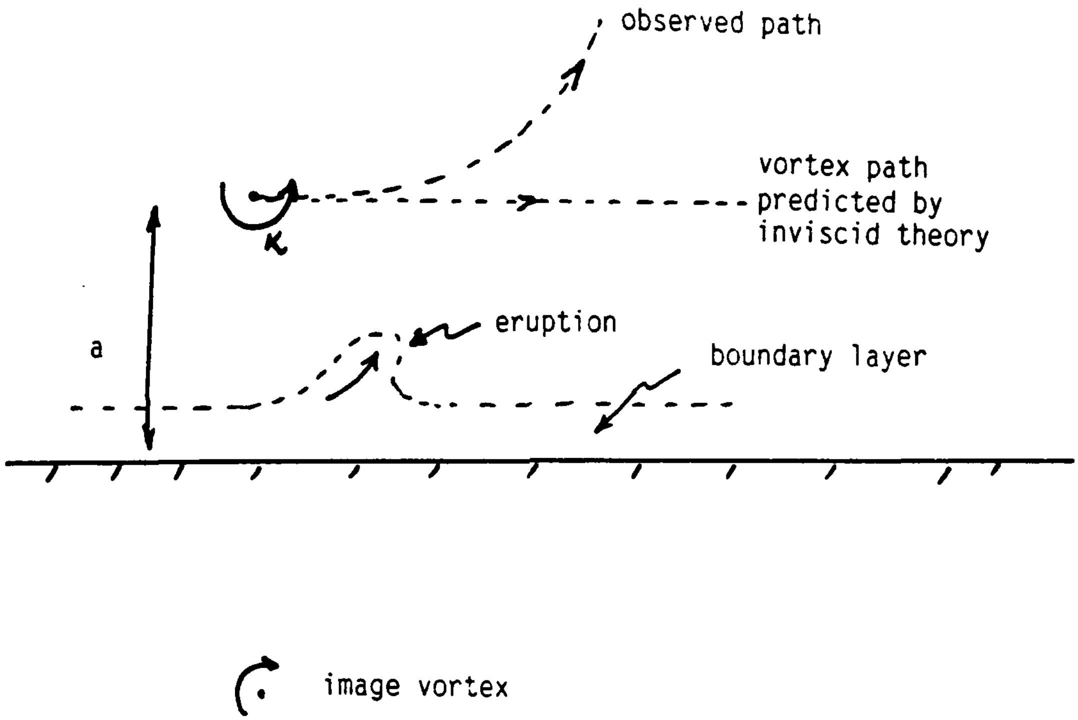


Figure 1. Geometry for the model problem.

boundary-layer eruption. In this case, a single two-dimensional vortex is placed in an otherwise stagnant flow above a plane wall. Inviscid theory predicts that such a vortex will remain at ^nstant height above the wall and be driven to the right at constant speed by the image vortex below the wall. However as time increases, separation occurs in the boundary-layer flow near the wall and the boundary layer erupts, ejecting a secondary vortex in the process. In the algorithms that have been developed over the past year,it has been possible to track the evolution of this eruption much further in time than was previously possible. Using interacting boundary-layer concepts the methods have been extended to treat the case of finite but large Reynolds numbers. Some preliminary results for a Reynolds number of 100,000 are shown in figure 2 for displacement thickness. A streamwise transformation has been used here to compress the region between upstream and downstream infinity to a finite range of 0 to 2. The sharply thickening displacement thickness shown in figure 2 at later times is typical of that encountered in strongly interacting flows as the interaction begins to develop. The present methods compute this evolution smoothly. A portion of this work will be reported at the AIAA 26th Aerospace Sciences meeting in Reno, Nevada, Jan. 1988 (Peridier and Walker,1988).

2.2 The Evolution of Hairpin Vortices in Shear

Recent experimental studies strongly suggest that the hairpin vortex plays an important, and possibly dominant, role in the dynamics of turbulent flows near walls. In this portion of the theoretical studies, various aspects of the motion of hairpin vortices near solid walls were studied. In particular, the following topics were of interest: (1) the nature of the evolution of hairpin vortices in a shear flow; (2) the type of flow induced near a wall by a convected hairpin vortex; (3) the character of the viscous response near a wall to the hairpin vortex motion and (4) the nature of the interation between two hairpin vortices.

During the past year, several computational studies have been carried out in support of the experimental studies of the evolution of hairpain vortices in a shear flow (Hon and Walker,1987). In these stu ies, a numerical precedure was developed to allow the accurate evaluation of the trajectory of a three-dimensional vortex for vortices having small cores. The integration method is based on a numerical approximation to the Biot-Savart integral; most existing vortex calculation methods have severe stability problems for vortices with small cores. The stability problem was overcome with the present technique and the methods were used to compute the evolution of convected vortex loops and hairpin vortices, both in a uniform flow and a shear flow above a wall. For the case of hairpin vortices evolving in a shear flow, a regenerative process was observed wherein secondary hairpin vortices form outboard of the

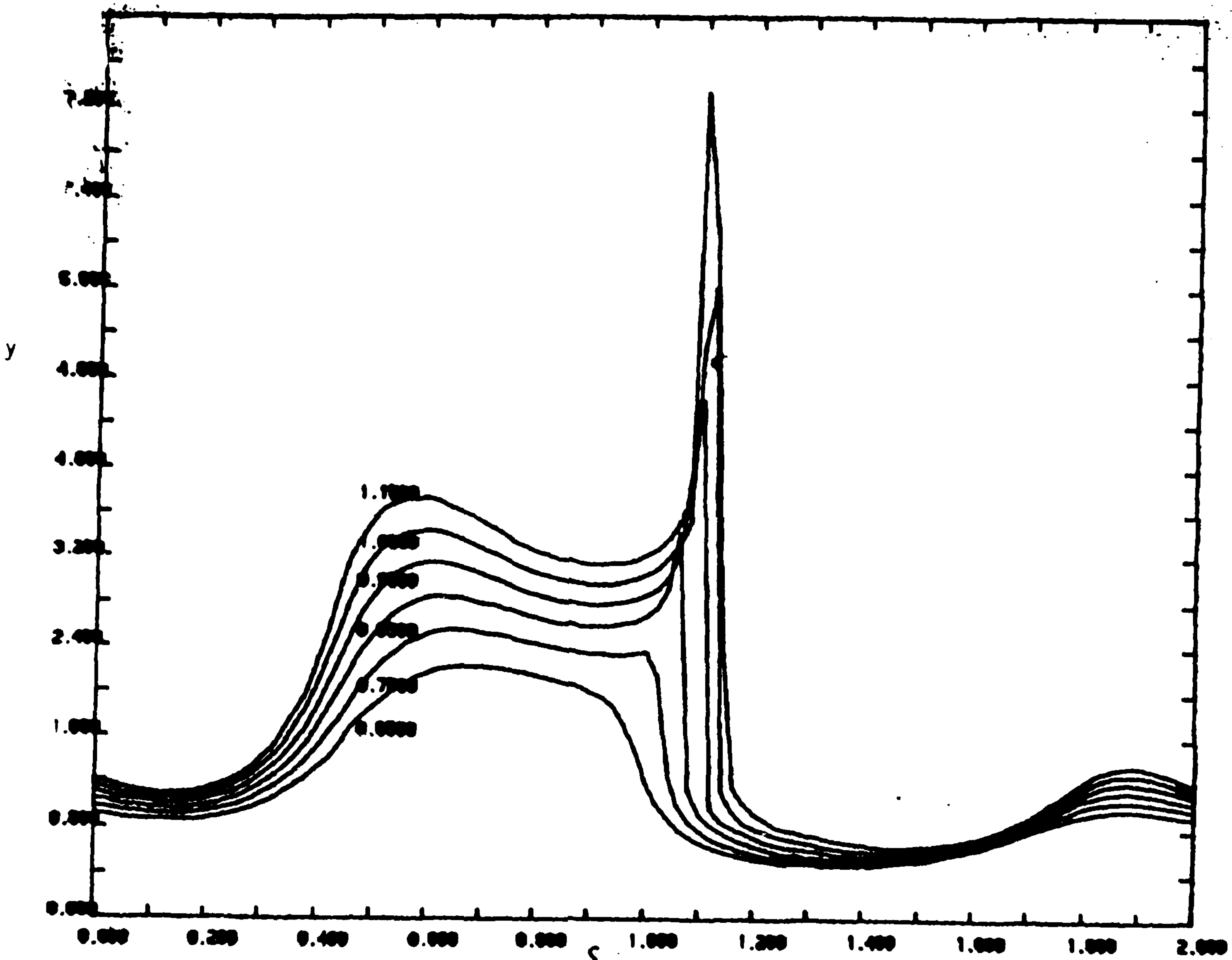


Figure 2. Temporal development of displacement thickness for Re = 10^5 .

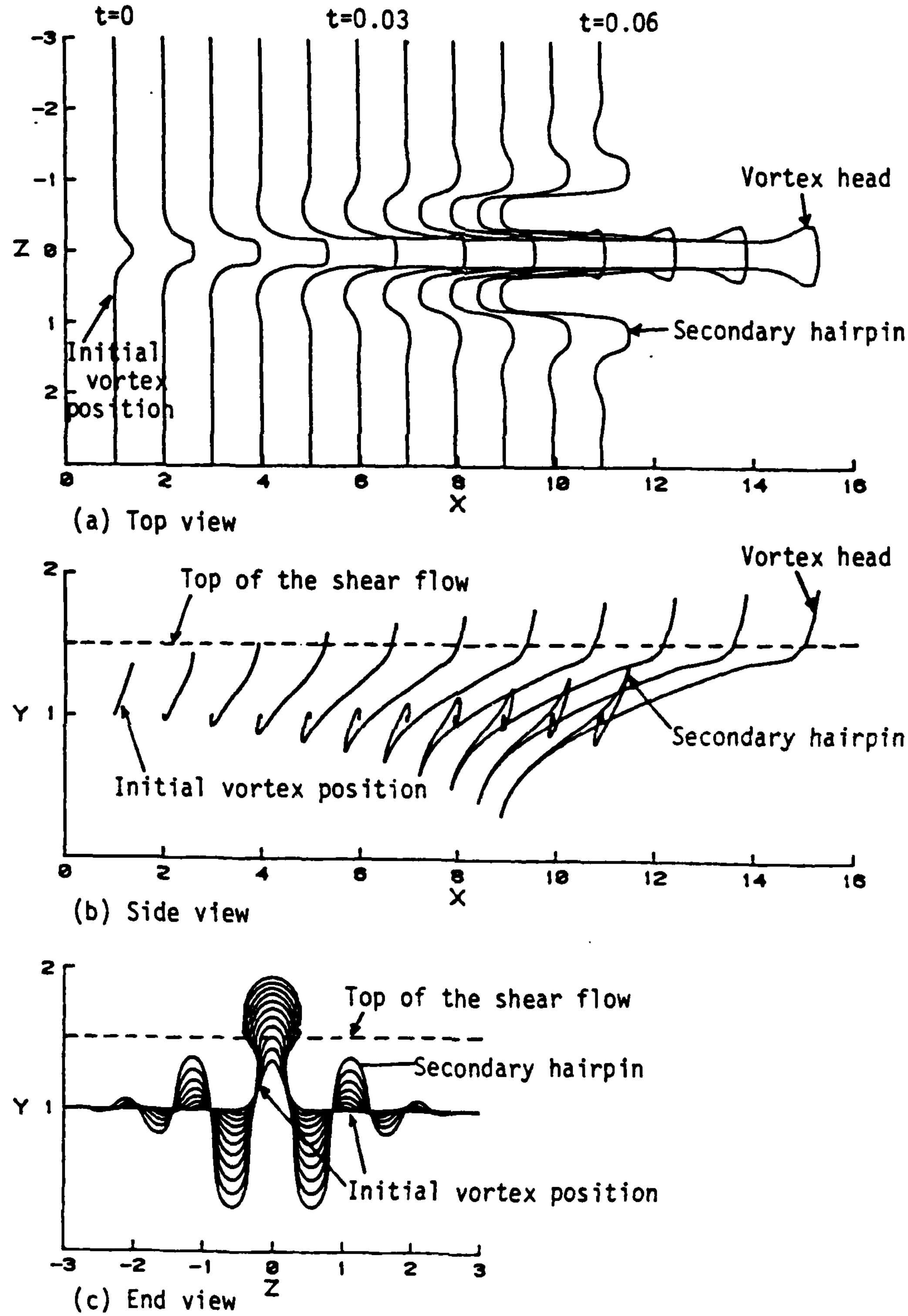


Figure 3. - Temporal development for a hairpin vortex in a shear flow (V=250). Case 6 (α=45°, A=0.5, β=20); the vortex position is plotted every 30 time steps (Δt=0.0002).

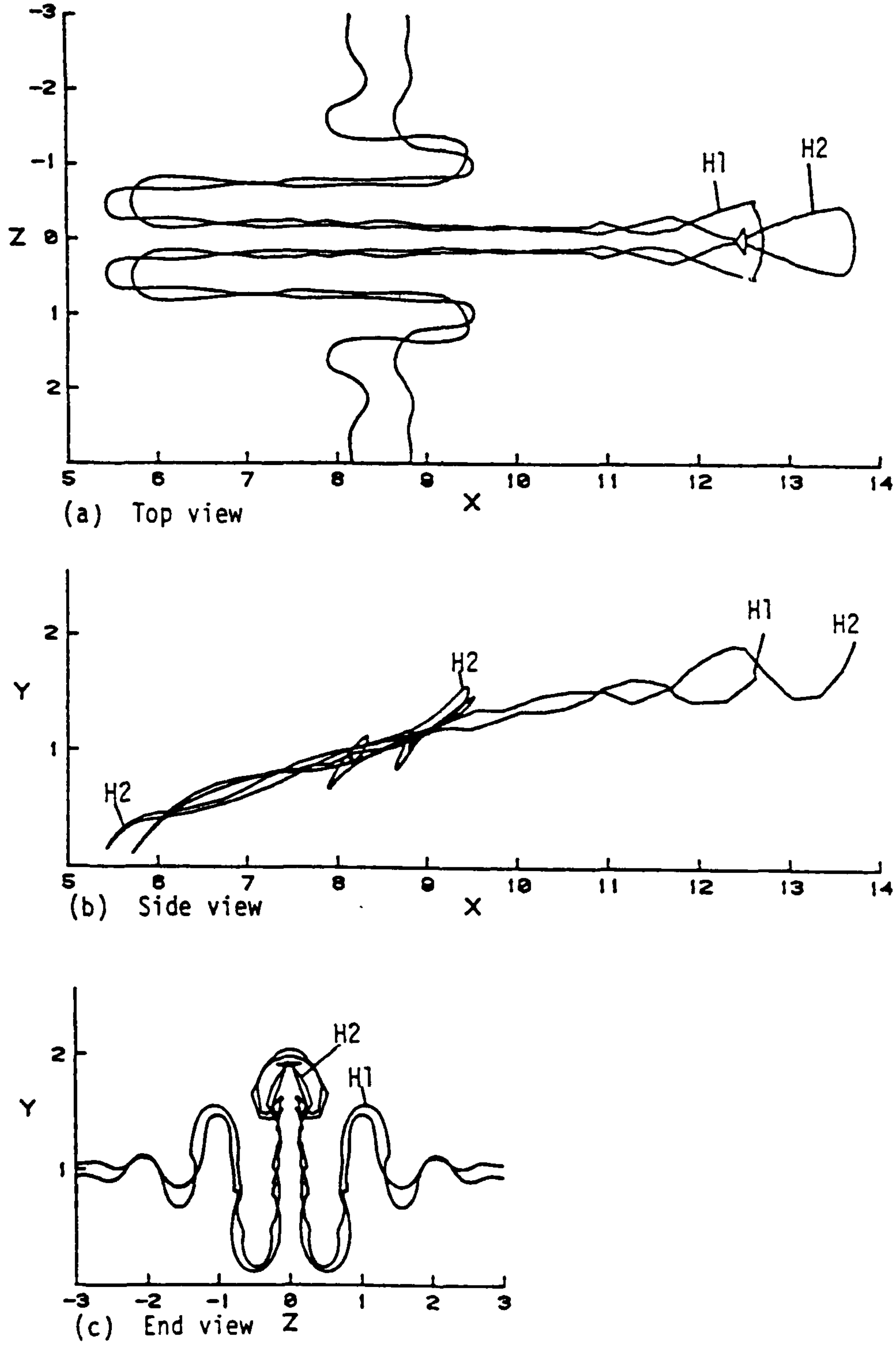


Figure 4. - Development of the two hairpin vortices at t=.048.

original hairpin vortex in a manner consistent with experimental observations. Some typical results for a hairpin vortex evolving in a shear flow are depicted in figure 3. Calculations for two interacting hairpin vortices, which are intially close to one another in a shear flow show that the vortices interact in a manner so as to reinforce one another. Some typical results for a pair of hairpin vortices are given in figure 4. Simulations were also carried out to compute the evolution of hydrogen bubble lines as a hairpin vortex passes and these calculations show that such vortices can give rise to wall-layer streaks in the turbulent boundary layer.

In a second phase of this study, the response was computed for a viscous flow near a wall due to the motion of a hairpin vortex above the wall. The results reveal that a complex, unsteady boundary-layer flow develops near the wall which ultimately evolves into a strong local outward growth. The final stages of this development are expected to lead to a viscous-layer eruption and the creation of a secondary hairpin vortex through a strong viscous-inviscid interaction with the outer flow. This mode of regeneration is believed to be the fundamental process of regeneration of new vorticity in the turblent boundary layer.

2.3 Eruptive Mechanisms for Turbulent Flows Near Walls

As a result of a large number of experimental studies carried out over the past three decades, it has been possible to identify a repeatable and cyclic porcess that takes place in the wall region of a turbulent boundary layer (Walker, Scharnhorst and Weigand,1986). A variety of questions still surround the cause and effect relationships of the observed phenomena but at present it is possible to give a general description of the evolution of the wall-layer flow. Here the term wall layer is used to denote the portion of the turbulent flow near the wall where the effects of viscosity are important. There are two main features which are known to be important in the dynamics of the wall-layer flow and these are the low-speed streaks and the bursting phenomenon. If observations are carried out for a fixed area of the wall in a turbulent boundary layer, the wall layer will be seen to be in the quiescent state for a majority of the total observation time; this terminology implies that during this period, the wall layer responds passively to events taking place in the outer region of the turbulent boundary layer and that no strong interactions are occuring with the outer flow. During the quiescent period, the low-speed streaks may be observed and typically have a mean spacing of 100 wall layer units. The streaks are elongated in the streamwise direction and typically have lengths on the order of 1000 wall-layer units. The cause of the wall-layer streaks is not generally agreed upon but recent studies (Acarlar and Smith,1987; Hon and Walker 1987) strongly suggest that the streaks are the signatures of hairpin vortices which are being convected over the the wall in the outer-layer flow above the wall layer.

While the wall layer is in the quiescent state, the time-dependent flow in the turbulent boundary layer may be considered to have a distinct double structure; that is there is a well defined wall layer where viscous effects are important and an outer layer containing a primarily inviscid (but rotational flow). Note that the boundary between the two regions is not distinct or static at some specific distance from the wall. As the cycle in the wall layer progresses the boundary between the inner and outer regions is continuously in motion; for example, in the sweep event, outer region fluid penetrates very close to the wall and then during the quiescent period the wall layer thickens continuously due to viscous diffusion. A principal characteristic of the quiescent period is that the outer flow strongly influences the developing wall-layer flow but no major interactions between the two flow regions occur.

Eventually the quiescent period is observed to terminate in the bursting process at isolated streamwise and spanwise locations. The phenomena is normally observed to be associated with a wall-layer streak and initiates with a liftup of the streak from the wall and an apparent oscillation of the streak in both the spanwise and normal directions. The process culminates with a violent ejection of wall-layer fluid into the outer layer; the ejection is rapidly followed by a swift movement of outer-layer fluid toward the wall in an event termed the "sweep". In the process, the chaotic motion due to the eruption is swept away and the wall-layer streaks re-appear but at relatively different spanwise locations; at this stage, a new quiescent period begins locally. The bursting process may be described as an unsteady viscous-inviscid interaction in which the wall-layer flow interacts strongly with the outer flow. The duration of this event is brief (relative to the average length of the quiescent period) but the event is nevertheless of major importance. The bursting process is the fundamental regenerative mechanism of turbulence production in which new vorticity from the wall layer is abruptly and intermittently introduced into the outer region of the turbulent boundary layer. It is therefore of interest to develop an understanding of the sequence of events and physical processes that lead to a local flow breakdown and subsequent eruption of the wall-layer flow. In this way, it may eventually be possible to intelligently interfere with the cycle in order to achieve a specific goal such as drag reduction or reduced noise levels in the turbulence.

During the past year the problem of the development of the time-dependent flow in the wall layer has been investigated on a theoretical basis. Numerical solutions have been obtained for the developing flow between low-speed streaks during a typical cycle in the wall-layer flow using a rather general set of model equations based on the wall-layer scalings and the unsteady Navier-Stokes equations. During the typical cycle an inflow-outflow type of boundary condition is assumed to persist at the edge of the wall layer as indicated schematically in figure 5. This is the type of motion that a moving hairpin might induce on the wall layer as it passes over the wall. Let W_1 be a flow speed which is representative of the strength of the imposed outer-flow velocities which lead to the pumping action depicted in figure 5. A characteristic Reynolds number may then be defined in terms of W_1 and the mean streak spacing. The calculated results show that there are at least two possible paths to breakdown of the flow structure depicted in figure 5. The first of these occurs for high Reynolds number flows and may be thought of as occuring when the pumping action is relatively strong (because the hairpin vortex in the outer flow is either particularly strong or very close to the wall). In this process, a violent and abrupt eruption of the flow near the wall occurs in the cross-flow plane as a consequence of the action of the pressure field induced by the vorticular motion just outside the wall layer. The phenomenon is depicted in figures 6 where instantaneous streamlines in the cross-flow plane are depicted shortly before breakdown. Here an unsteady separation has occured in the cross-flow plane and the flow is evolving rapidly toward interaction on the right side of the separated region; here the flow will erupt in a very narrow band and the entire flow structure depicted in figure 5 will breakdown on a time scale which is compatible with measured bursting periods.

As the characteristic Reynolds number is decreased (and the strength of the pumping action at the edge of the wall layer diminishes) the tendency for the flow in the cross-flow plane to become violently eruptive diminishes and a new route to breakdown comes into play. In this mechanism, an inflectional behavior begins to evolve in the the streamwise velocity profile near the low-speed streak in a manner which is expected to lead to s strong local instability of the flow. Some typical results are depicted in figures 7. In these figures, the instantaneous streamlines in the crossflow plane are shown along with the instantaneous streamwise velocity profiles at selected stations across the span. It may be observed that an eddy develops near the low-speed streak at $z^+ = 0$ in the cross-flow plane; this separated region slowly evolves toward an essentially steady state as the cycle progresses. For the streamwise velocity profiles, the solid lines denote the instantaneous streamwise profile at that location across the span while the dotted profile is an average profile across the span at that instant. It may be observed that the streamwise velocity near the streak is in deficit; as we move progressively across the span, the streamwise velocity becomes in excess of the dotted profile. The main feature to note in this development is that the streamwise profiles just to the right of the streak begin to develop a pronounced inflectional character as the cycle progresses. This is clearly associated with the region of reversed flow in the cross-flow

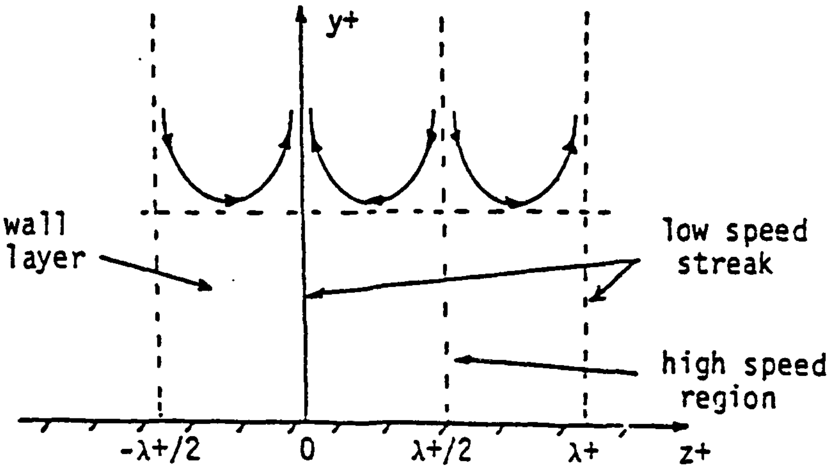
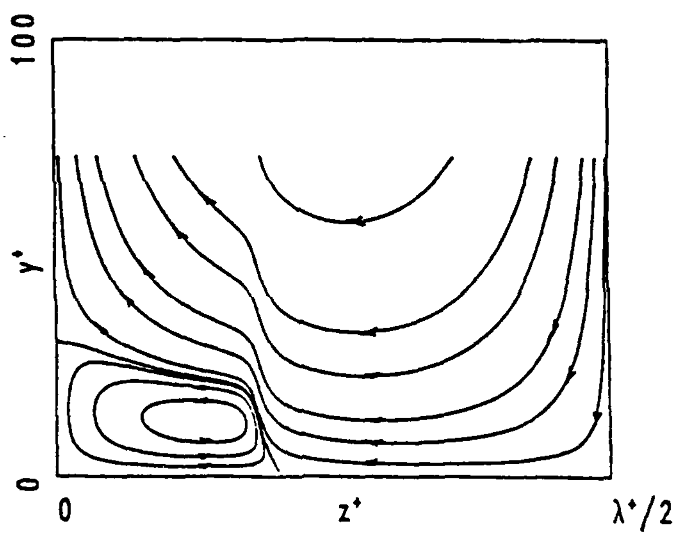
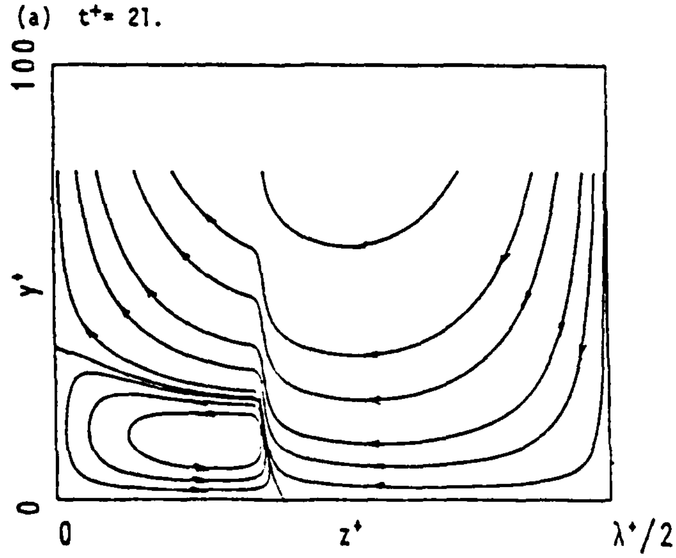


Figure 5. Schematic diagram of the assumed wall-layer structure during a typical quiescent period.



(a) $t^{+}= 21.$



(b) $t^{+}=22.25.$

Figure 6. Instantaneous streamlines in the cross-flow plane for the limit problem $Re_{\lambda}\to\infty$.

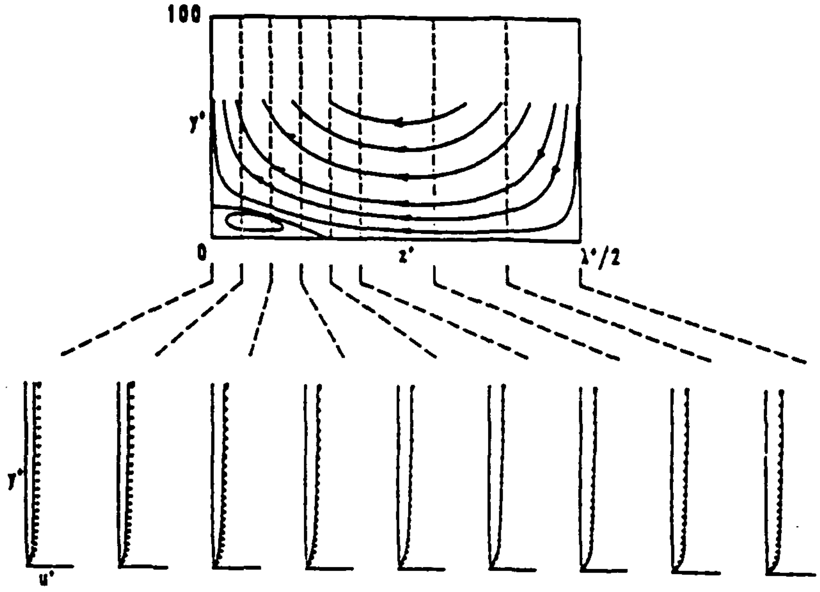


Figure 7(a) t^{+}-15.

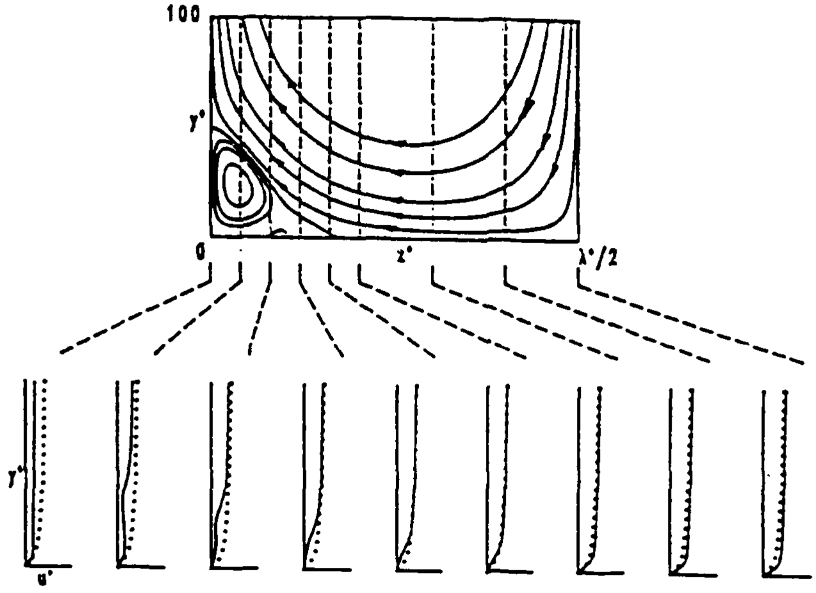
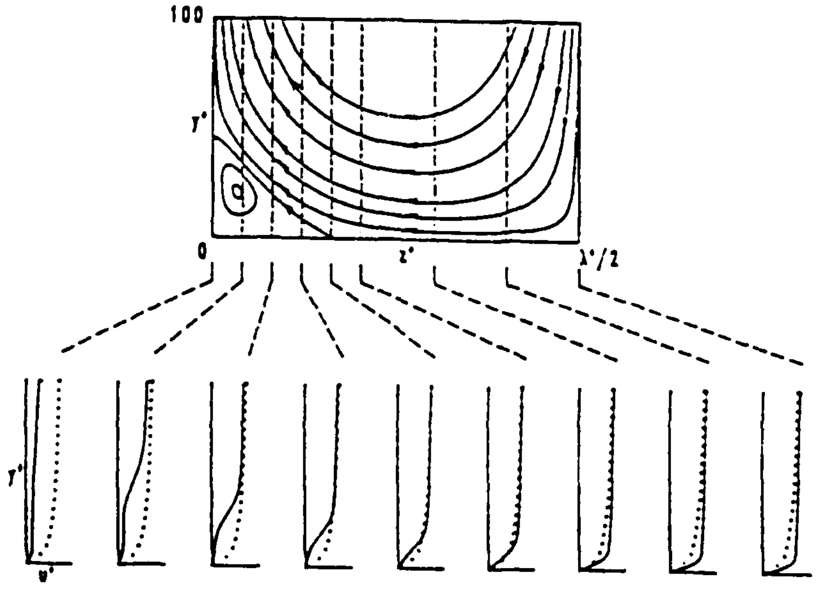


Figure 7(b) t^{+}=40.



7 (c) t^{+}=100.

Figure 7. Cross-flow plane streamlines and streamwise velocity profiles at various times for Re_{λ}=509.

plane. Experiments strongly suggest that the development of such a streamwise profile is the precursor of local flow breakdown.

3. HIGHLIGHTS OF EXPERIMENTAL PROGRESS

IDENTIFICATION OF HAIRPIN VORTICES IN TURBULENT BOUNDARY LAYERS USING TWO-DIMENSIONAL CORRELATION TECHNIQUES

Over the past several decades it has been shown that turbulence consists of a complicated process of vorticity generation, transfer, and dissipation which is generally accepted to occur in discrete events termed bursts; these bursts are widely believed to be precipitated by discrete vortex flow structures within the flow. The accepted scenario is that the "bursts" then give rise to new vortex flow "structures", which precipitate more "bursting" behavior. The form of the vortex flow structures which precipitate the bursting behavior and those which are generated by the bursting have been the subject of much debate and extensive research. The most likely suggestion is that "hairpin" vortices are the dominant form of flow structure. However, this premise is based primarily on qualitative flow visualization and analytical simulations; quantitative, empirical detection of such structures has not been done. The present study describes recent progress in the use of image processing of hydrogen bubble flow visualization to establish velocity flow-field data for empirically synthesized hairpin vortices, which is then employed to search for comparable vortex structures in the wall region of a turbulent boundary layer using pattern recognition techniques.

To provide the basis for the pattern recognition approaches, the Lehigh experimental program has developed techniques which allow instantaneous velocity profile data to be established from flow visualization data [Lu & Smith, 1985]. In addition, recent programatic efforts have developed the capacity to experimentally generate controlled hairpin vortices [Acarlar & Smith, 1987a, 1987b]. Employing the image processing techniques described in Lu & Smith (1985) with controlled hairpin vortex generation techniques described in Acarlar & Smith (1987a, 1987b), we have been able to establish the cyclical velocity behavior for hairpin vortices. This now gives us the necessary tools to conduct a quantitative "search" for hairpin flow structures in turbulent boundary layers.

The results obtained by image processing of selected hydrogen bubble visualizations of a cyclically generated hairpin vortex are shown in figures 8 and 9. The right side of figures 8 and 9 is a series of scenes taken from a hydrogen bubble flow visualization sequence of the passage of a hairpin vortex (with the bubble-wire located on the plane of symmetry of the hairpin vortex) from left to right; the hairpin vortices shown are from a vortex street generated by periodic shedding from a hemisphere placed in a subcritical laminar boundary layer. In each sequence, the head of the hairpin vortex appears at the left and passes across the screen, followed by the streamwise legs of the vortex. Note that the pictures in figures 8 and 9 are digitized pictures displayed on the screen of a Gould 8500 image processing system.

Using the entire visualization sequences, instantaneous velocity profile behavior is established using time-of-flight techniques described in Lu & Smith (1985), yielding the sequence of velocity profiles and profile-derived results shown at the left in figures 8 and 9. The profiles advance in time from left-to-right; each profile is 1/60 second apart. Note that in addition to the basic velocity profile information, profiles of the corresponding fluctuating, derivative, and burst-associated statistics are shown.

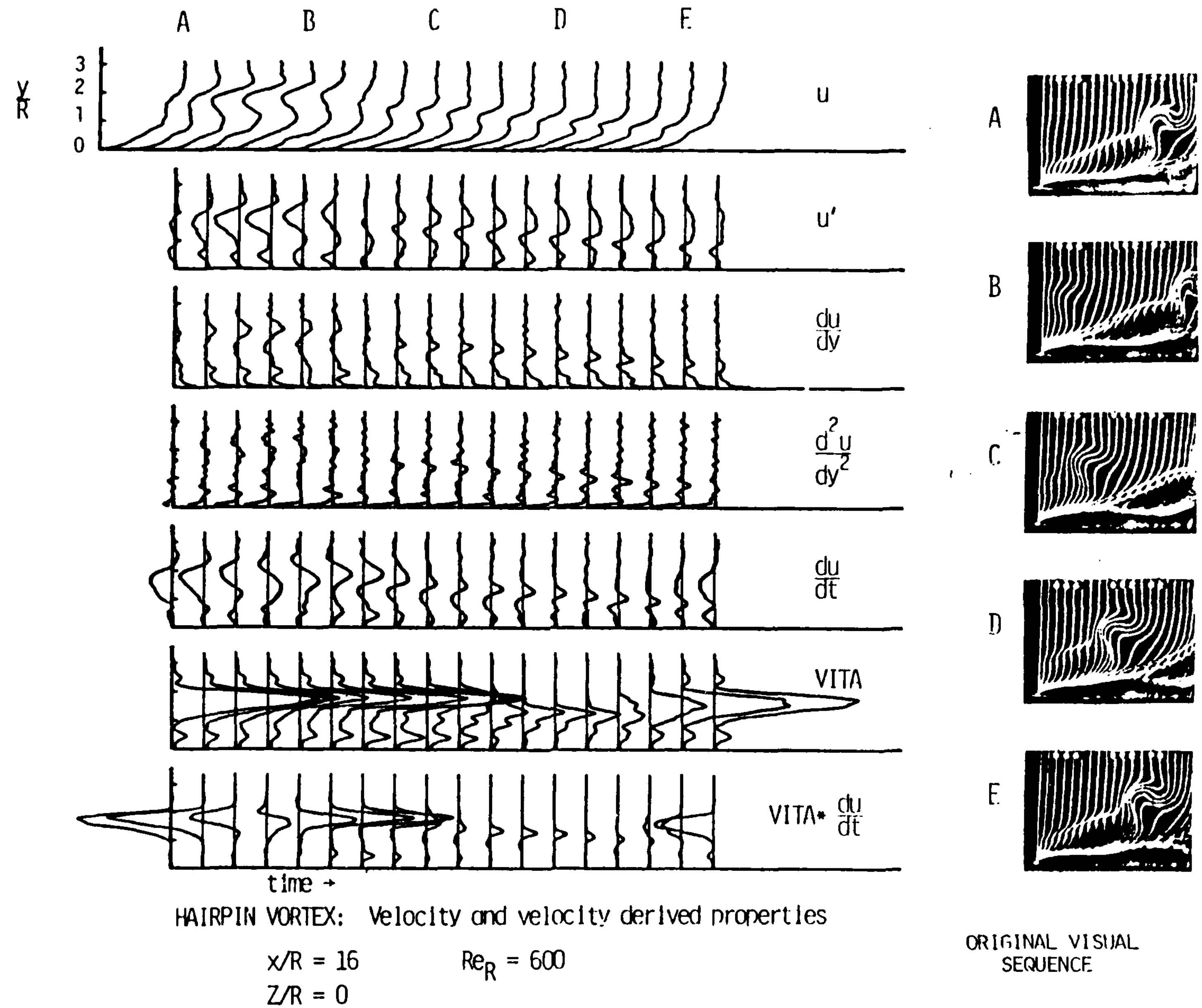


Figure 8. Velocity derived properties obtained from image processing of hairpin vortex flow visualization.

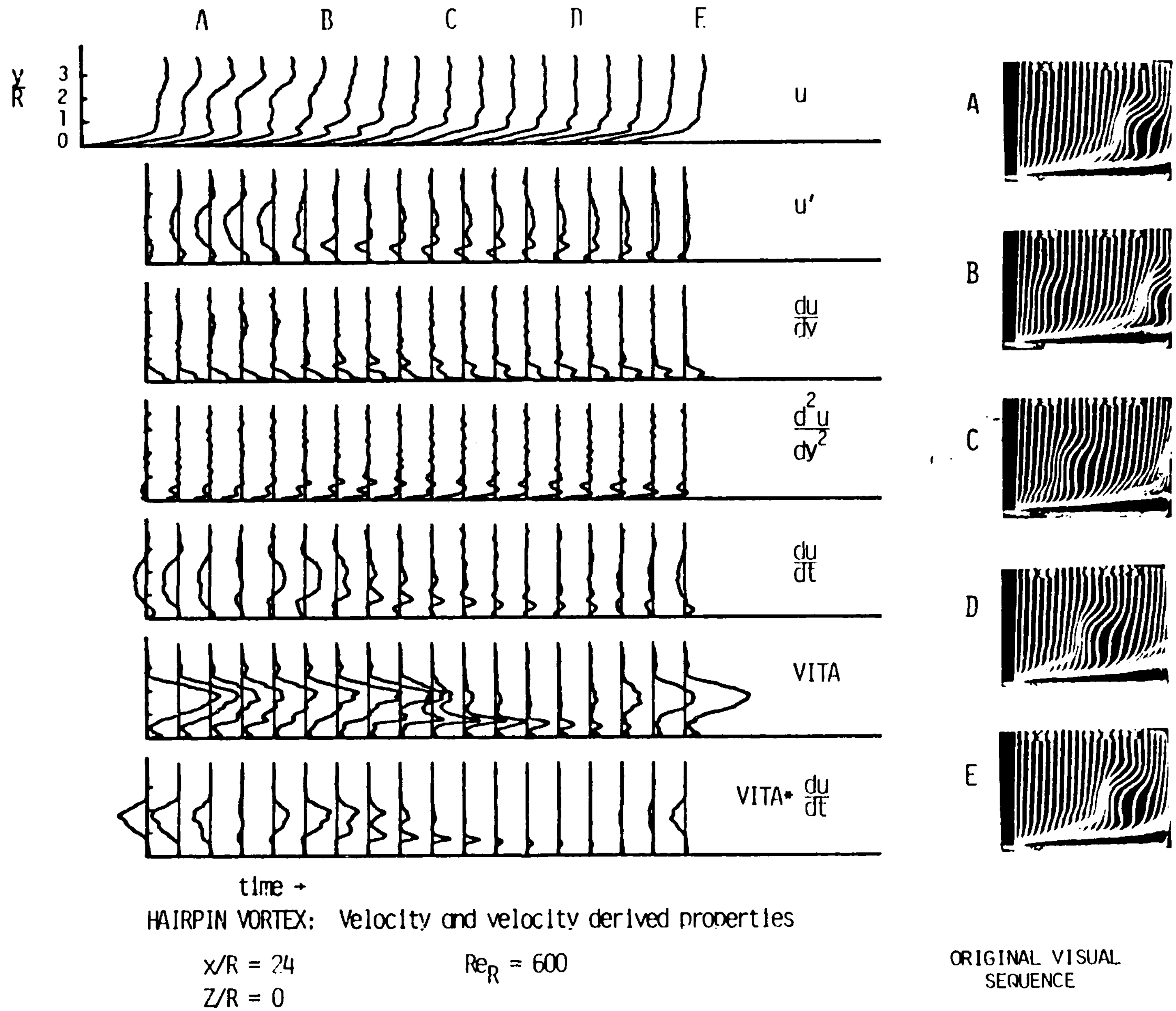


Figure 9. Velocity derived properties obtained from image processing of hairpin vortex flow visualization.

To provide a more compact method for presentation of profile data such as presented in figures 8 and 9, the image processing system is employed to convert the data to two-dimensional intensity images which use grey-level shading as the indicator of velocity (or other property) magnitude. The following figure illustrates how this mode of presentation is accomplished.

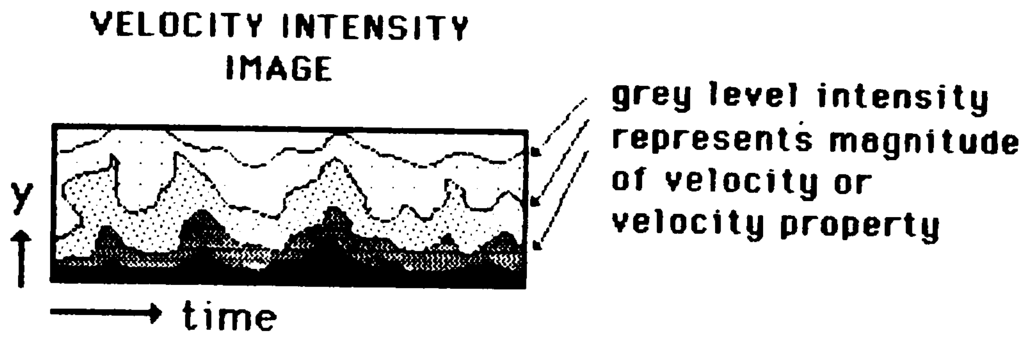


Figure 10 illustrates how the instantaneous hairpin vortex velocity profile data shown in figures 8 and 9, as well as typical result for a fully turbulent boundary layer ($0 \leq y^+ \leq 160$), appear when presented as intensity images. For the hairpin images (shown at the bottom of figure 10), note how the highest velocity excursions (brightest regions) and the lowest velocity excursions (darkest regions) modify with downstream location of the bubble wire location, and how the highest and lowest velocity excursions appear relatively consistent and in-phase across the entire field of view.

Visual comparison of the hairpin images with the image created from turbulent boundary layer data (upper image in figure 10) indicates a marked similarity.

The visual recognition of the similarity of the intensity images provides further support for the presence and importance of hairpin-type structures within turbulent boundary layers. However, in order to prove the presence or non-presence of hairpin vortices, the recognition of the appropriate patterns must be removed from the realm of subjective identification, and the recognition process must be established on a quantitative and statistical basis. In order to provide a quantification of the identification process, several different two-dimensional correlation approaches have been examined for use in identifying typical hairpin patterns within the fully-turbulent flow field. Using the velocity-time history data obtained from the image processing work, the different pattern recognition approaches have been examined using the hairpin vortex velocity-time histories as matching patterns and the velocity time-history for a turbulent boundary layer as the reference pattern.

After much study, the two most promising approaches appear to be 1) template matching, and 2) a modified, two-dimensional orthogonal decomposition-matching approach. The template matching approach is illustrated in figure 11. Basically, the hairpin velocity-time pattern is employed as a "template", which is then used to two-dimensionally "search" the

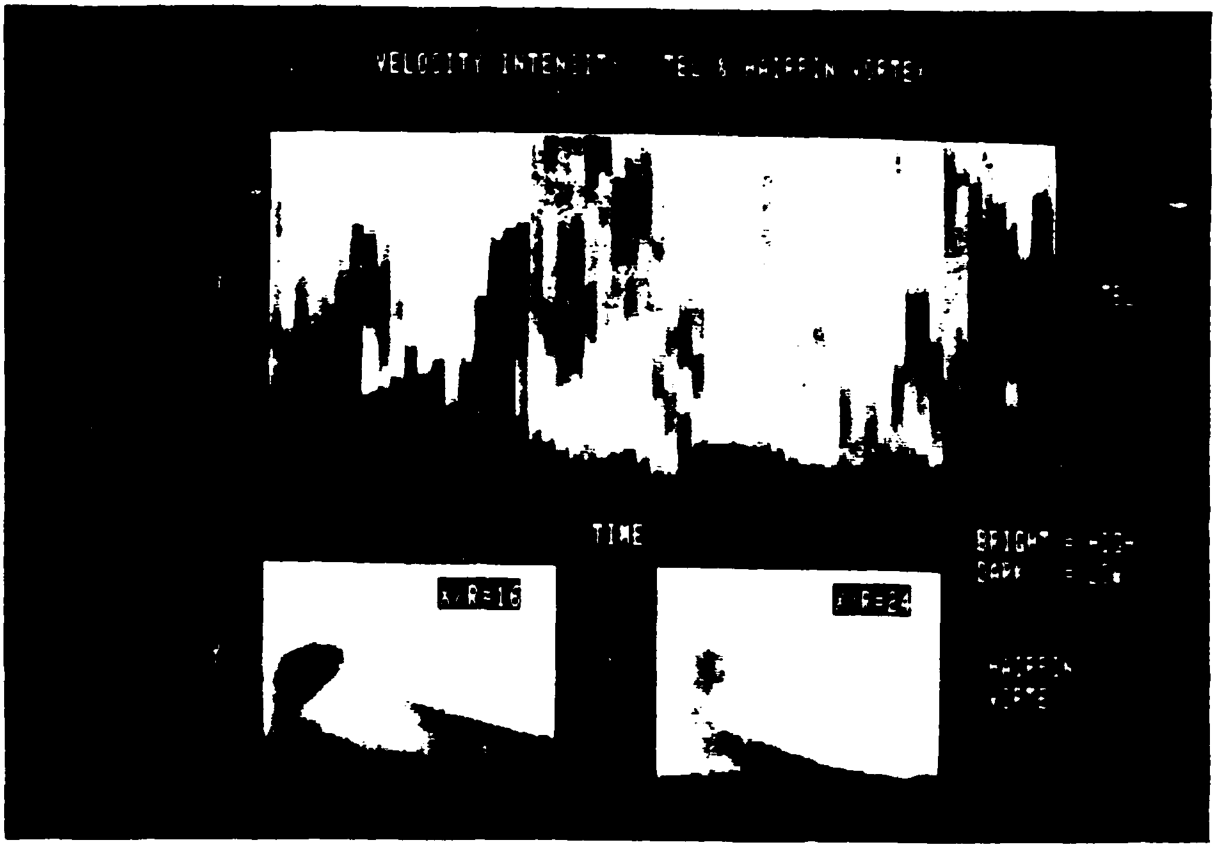


Figure 10. Intensity images of velocity-time histories for 1) Turbulent boundary layer (Top) and 2) hairpin vortex (bottom two images).

velocity-time history of the turbulent boundary layer for comparable patterns using two-dimensional correlations. The result is a correlation coefficient plot, similar to that shown at the bottom of figure 11. Identification of the peaks in the correlation coefficient then indicate the location of positive "matches", which are then cross-compared with other modes of identification, such as visual detections from the original visualization sequence, VITA detection approaches, etc. Problems with this approach are that the scale of the template pattern and the reference pattern are unspecified. This requires that the template pattern by varied in the vertical displacement (y) and time (t) scale. An example of a typical output of such a search in which the y-scale of the template (hairpin) pattern was varied in increments of 10% of full scale is shown in figure 12. Clearly, this is a very cumbersome process which makes for numerous and lengthy calculations. The results of this technique are very promising, however, and methods to expedite the identification process are being developed.

A second pattern identification approach which shows promise is the use of the Lumley orthogonal decomposition approach to determine the capacity of hairpin-derived velocity-time histories to "match" the dominant characteristics of fully turbulent flow. Initially, the hairpin velocity-time histories are decomposed into their dominant eigenvalue modes. Then a sequence of the dominant eigenvalue modes are determined for a fixed-size two-dimensional "window" of data from a turbulent boundary layer velocity-time history, where the window is incrementally moved across the entire turbulence record. The latter result is a sequence of dominant eigenmodes for the local turbulence "window" as a function of window location within the turbulence data record. The eigenmode patterns from the hairpin data are then compared via visual and cross-correlation approaches to establish where the hairpin eigenmodes best "match" the data within the turbulence "window". Preliminary results indicate that this approach gives a high degree of correlation with the template matching pattern recognition and visual identification (from the original visualization sequence) of "bursting". This modified decomposition approach is a unique technique which shows significant promise for ferreting out dominant, organized flow structure characteristics from a seemingly chaotic background of flow structures. The details and effectiveness of this approach will be covered next year in the final report.

PROCESS OF TEMPLATE CORRELATION

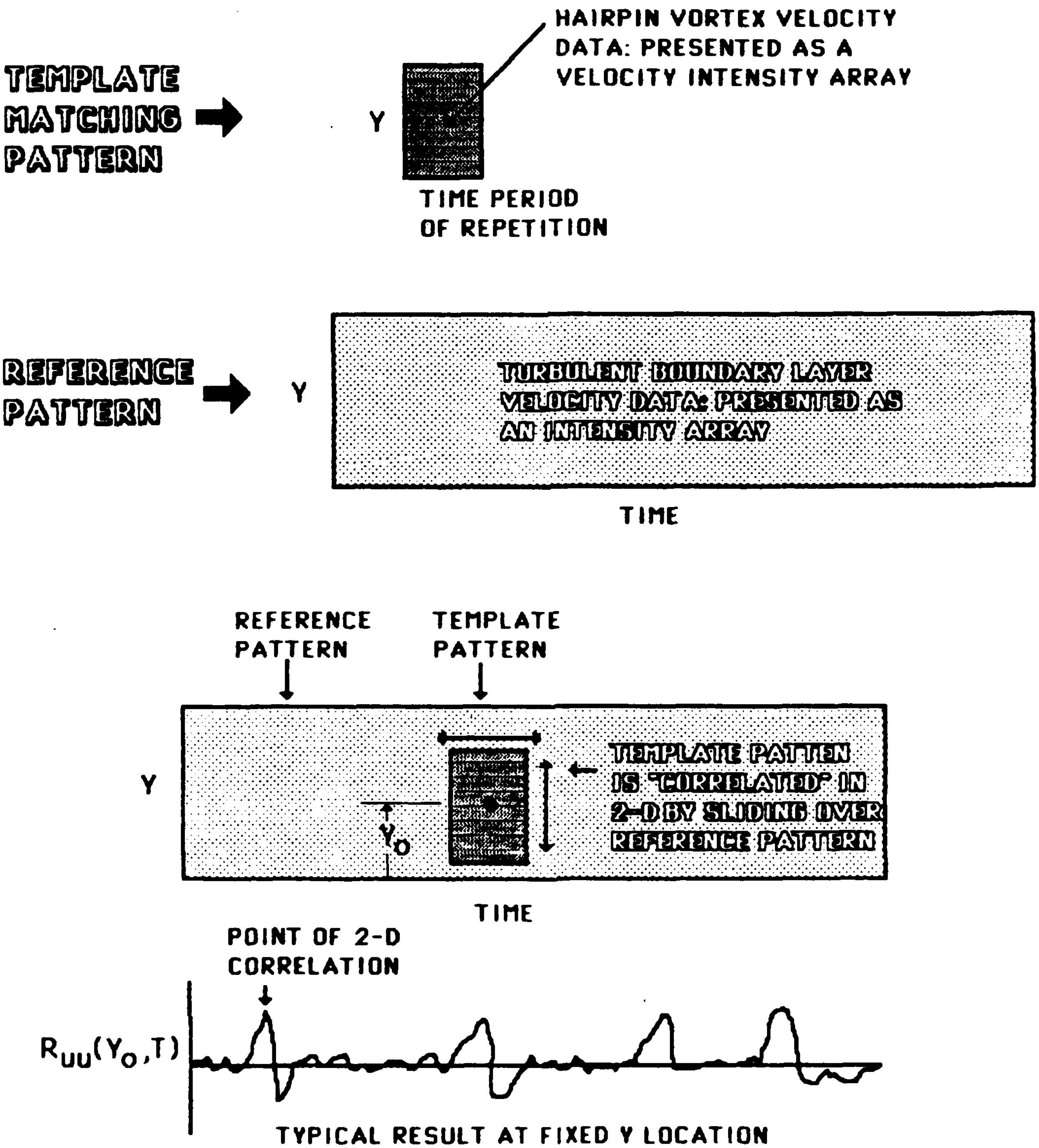


Figure 11. Method of template matching of hairpin vortex pattern vs. turbulent boundary layer results.

4. ASSOCIATED PUBLICATIONS, PRESENTATIONS, AND THESES
(During the present AFOSR contract period)

A. Publications

1. Ersoy, S. and Walker, J.D.A., "Viscous flow induced by counter-rotating vortices", Physics of Fluids, vol. 28, p. 2687, (1985).

2. Lu, L.J. and Smith, C.R., "Image processing of hydrogen bubble flow visualization for determination of turbulence statistics and bursting characteristics", Exp. in Fluids, vol. 3, p. 349, (1985).

3. Wei, T. and Smith, C.R., "Secondary vortices in the wake of circular cylinders", J. Fluid Mech., vol. 169, p. 513, (1986).

4. Bacher, E.V. and Smith, C.R., "Turbulent boundary-layer modification by surface riblets", AIAA J., vol. 24, no. 8, p. 1382, (1986).

5. Johansen, J.B. and Smith, C.R., "The effects of cylindrical surface modifications on turbulent boundary layers", AIAA J., vol. 24, no. 7, p. 1081, (1986).

6. Walker, J.D.A., Scharnhorst, R.K., and Weigand, G.G., "Wall layer models for the calculation of velocity and heat transfer in turbulent boundary layers", AIAA paper 86-0213, (1986).

7. Ersoy, S. and Walker, J.D.A., "The flow induced at a wall by a vortex pair", AIAA paper 85-1583, also AIAA J., 24, pp. 1597-1605, (1986).

8. Lu, L.J. and Smith, C.R., "Application of image processing of hydrogen bubble flow visualization for evaluation of turbulence characteristics and flow structure", in Flow Visualization IV, C. Veret, ed., Hemisphere, (1986).

9. Acarlar, M.S. and Smith, C.R., "A study of hairpin vortices in a laminar boundary layer. Part I. Hairpin vortices generated by a hemisphere protuberance", J. Fluid Mech., vol. 175, p. 1, (1987).

10. Acarlar, M.S. and Smith, C.R., "A study of hairpin vortices in a laminar boundary layer. Part II. Hairpin vortices generated by fluid injection", J. Fluid Mech., vol. 175, p. 43, (1987).

11. Walker, J.D.A., Smith, C.R., Cerra, A.W., and Doligalski, T.L., "The viscous flow due to an impacting vortex ring", J. Fluid Mech., vol. p. , (1987).

12. Ersoy, S. and Walker, J.D.A., "The boundary layer due to a three-dimensional vortex loop", in press, J. Fluid Mech.

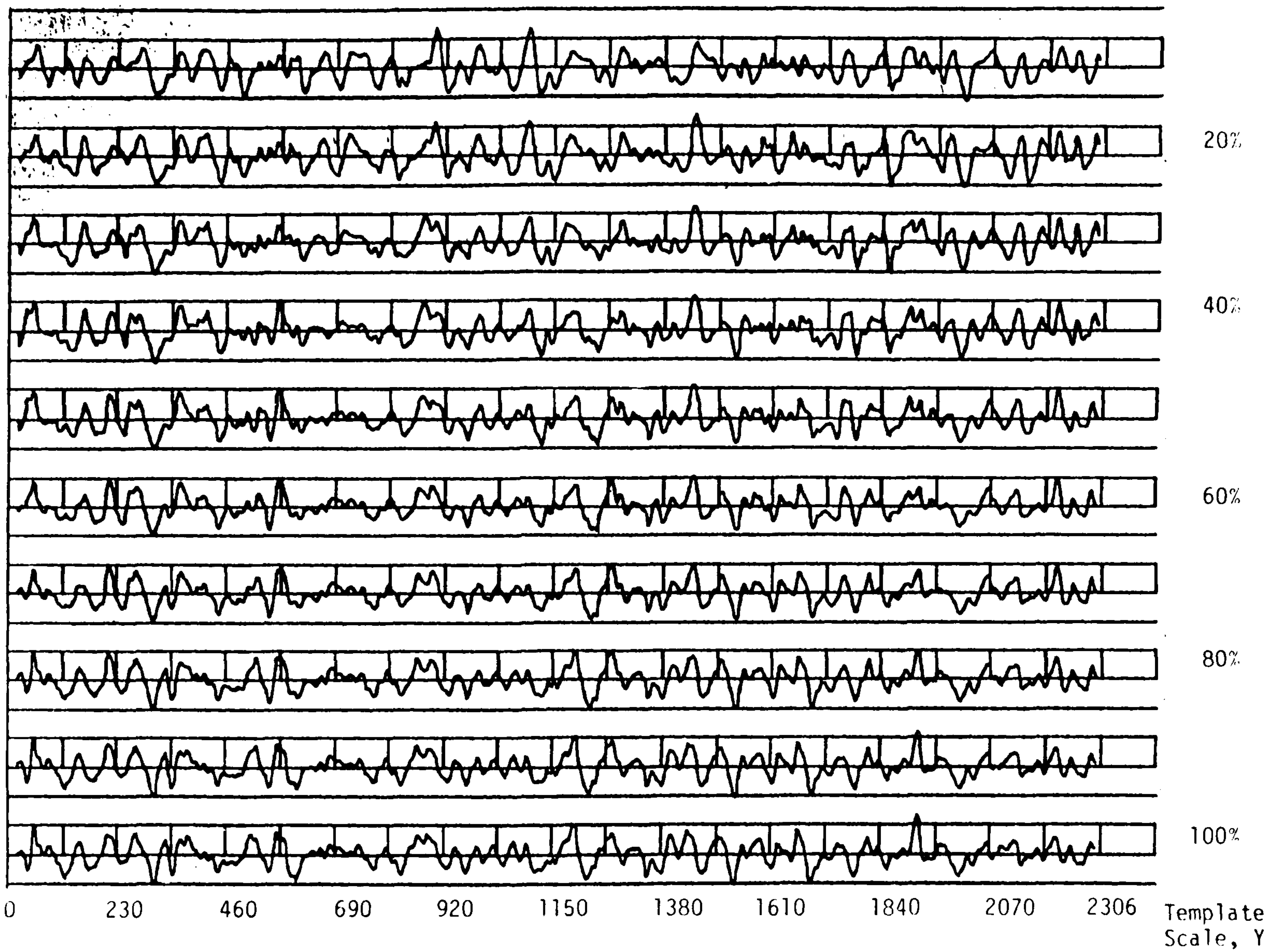


Figure 12. Example of template matching of hairpin pattern vs. turbulent boundary layer. Hairpin template varied by 10% increments in y-scale.

13. Ersoy, S. and Walker, J.D.A., "The viscous flow induced near a wall by counter-rotating vortex pairs and vortex loops", Technical Report No. FM-8, Department of Mechanical Engineering and Mechanics, Lehigh University, June 1985.

14. Walker, J.D.A., and Scharnhorst, R.K., "The Ξ function", Report No. FM-9, Department of Mechanical Engineering and Mechanics, Lehigh University, January 1986.

15. Smith, C.R., "Computer-aided flow visualization", Chapter in <u>Handbook of Flow Visualization</u>, ed. W.J. Yang, Hemisphere Pub. Co., (in press).

16. Hon, T.L. and Walker, J.D.A., "Analysis of the motions and effects of hairpin vortices", Technical Report FM-11, Dept. of Mechanical Engineering and Mechanics, Lehigh University, June 1987.

17. Hon, T.L. and Walker, J.D.A., "The influence of a moving hairpin vortex", to appear in Computers and Fluids.

18. Walker, J.D.A., Scharnhorst, R.K. and Weigand, G.G., "A wall layer model for the velocity profile in turbulent flows", to appear in AIAA J.

19. Walker, J.D.A., Ece, M.C. and Werle, M.J., "An embedded function approach for turbulent flow prediction", AIAA Paper 87-1464.

20. Walker, J.D.A., Werle, M.J. and Ece, M.C., "An embedded function approach for the calculation of turbulent flow near walls", UTRC Report, UTRC86-78, March 1987.

21. Bogucz, E. and Walker, J.D.A., "The turbulent near wake at a sharp trailing edge", submitted to J. Fluid Mechanics, in review.

22. Walker, J.D.A. and Herzog, S., "Eruption mechanisms for turbulent flows near walls", paper to be presented at the 2nd International Symposium on Transport Phenomena in Turbulent Flows, to be held at the University of Tokyo, October 25-29, 1987, and to appear in the Conference Proceedings.

B. Presentations

C.R. Smith

1. "A combined visualization-anemometry study of triangular drag reducing mechanisms of triangular surface modifications", AIAA Shear Flow Control Conference, March 13, 1985.

2. "The effects of cylindrical surface modifications on turbulent boundary layers", AIAA Shear Flow Control Conference, March 13, 1985.

3. "An experimental study of hairpin vortices as a causative agent of near-wall turbulent flow structure", Invited Lecture, 22nd Society of Engineering Sciences, Penn State University, Oct. 7, 1985.

4. "Hairpin vortices in turbulent boundary layers: the implications for reducing surface drag", Invited Talk, DOD Drag Reduction Symposium, National Academy of Sciences, Washington, D.C., Oct. 23, 1985.

5. "A correlation of velocity flow field behavior with flow visualization data during turbulent bursting", 38th meeting of div. fluid dynamics, Amer. Phys. Soc., Nov. 25, 1985.

6. "Search for structure in hydrodynamics: applications of flow visualization and image processing", Invited Seminar, Mechanical Engineering Seminar Series, Penn State University, Nov. 6, 1986.

7. "Three-dimensional vortices in the wake of circular cylinders", invited presentation, Workshop on Bluff-Body Near-Wake Instabilities, Ohio State University, November 22, 1986.

8. "The search for hairpin vortex flow structures in turbulent boundary layers", 39th meeting of div. fluid dynamics, Amer. Phys. Soc., Nov. 25, 1986.

9. "Wall-layer flow structure: Empirical simulation and evaluation", Invited lecture, Workshop on Turbulent Wall Layers, University of Texas, 13 February, 1987.

10. "Application of image processing of hydrogen bubble flow visualization for evaluation of turbulence characteristics and flow structure", Invited Seminar, Applied Mechanics Seminar, University of Southern California, April 10, 1987.

11. "Flow structure in the wall region of turbulent boundary layers including empirical simulations", Invited Seminar, Fluid Mechanics Seminar Series, Stanford University, April 14, 1987.

J.D.A. Walker

1. "Asymptotic theory of turbulence at a trailing edge", Invited presentation, Applied Mathematics Conference, Rensselaer Polytechnic Institute, June 1-2, 1985.

2. "Some aspects of turbulence modeling", Invited keynote address to the SSME Computational Third Working Group Meeting, George C. Marshall Space Flight Center, Alabama, June 11-14, 1985.

3. "The flow induced at a wall by a vortex pair" presentation at the 18th AIAA Fluid Dynamics, Plasma Dynamics and Laser Conference, Cincinnati, Ohio, July 16-18, 1985.

4. "The boundary layer induced by a three-dimensional vortex loop", presentation at the 38th Meeting of the American Physical Society, Division of Fluid Dynamics, University of Arizona, November 24-26, 1985.

5. "The evolution of a hairpin vortex in a shear flow", presentation at the 38th Meeting of the American Physical Society, Division of Fluid Dynamics, University of Arizona, November 24-26, 1985.

6. "Wall layer models for the calculation of velocity and heat transfer in turbulent boundary layers", presentation at the AIAA 24th Aerospace Meeting, Reno, Nevada, January 6-8, 1985.

7. "Boundary layer eruptions induced by vortex motion", Invited Seminar, NASA Lewis Research Center, Cleveland, Ohio, March 20, 1986.

8. "Invited participant, Workshop on Atmospheric Turbulence Relative to Aviation, Missile and Space Programs, NASA Langley Research Center, Hampton, Virginia, April 2-4, 1986.

9. "Computational enhancements to viscous flow predictions" (with J.E. Carter, United Technologies Research Center), presentation to SSME Computational Fluid Dynamics Fourth Working Group Meeting, George C. Marshall Space Flight Center, Huntsville, Alabama, April 10, 1986.

10. "Turbulent flow at a sharp trailing edge", NASA Lewis Research Center, Cleveland, Ohio, July 25, 1986.

11. "Some apsects of three-dimensional vortex motion", NASA Lewis Research Center, Cleveland, Ohio, August 8, 1986.

12. "Calculation of turbulent flows near walls", NASA Lewis Research Center, Cleveland, Ohio, August 15, 1986.

13. "Mechanism for turbulence prediction near a wall", presentation at the 39th Annual Meeting of the American Physical Society, Division of Fluid Dynamics, Ohio State University, November 23-25, 1986.

14. "Viscous flow induced by a hairpin vortex convecting in a shear flow", presentation at the 39th Annual Meeting of the American Physical Society, Division of Fluid Dynamics, Ohio State University, November 23-25, 1986.

15. "Embedded function methods for turbulent flow prediction", NASA Langley Research Center, Dec. 4, 1987.

16. Invited participant, Turbulent Wall Layer Workshop, "Physical mechanisms leading to eruptions", U. of Texas at Austin, Feb. 12-13, 1987.

17. "An embedded function approach for turbulent flow prediction", AIAA 19th Fluid Dynamics Conference, Honolulu, Hawaii, June 8-10, 1987.

18. "An embedded function method for the calculation of turbulent flow near walls", NASA Lewis Research Center, Cleveland, Ohio, July 22, 1987.

19. "The influence of a moving hairpin vortex", R.T. Davis Symposium, Cincinnati, Ohio, June 12, 1987.

20. "Effects of a hairpin vortex convected in a shear flow", NASA Lewis Research Center, July 14, 1987.

21. "Mechanisms for wall layer eruptions", NASA Lewis Research Center, July 2, 1987.

C. Theses

Completed Theses

1. Ersoy, S., "The flow induced near a wall by counter-rotating vortex pairs and vortex loops", Ph.D., Lehigh University, June 1985.

2. Ece, M.C., "An analysis of turbulent thermal trailing edge flows", Ph.D., Lehigh University, June 1986.

3. Hon, T.L., "The boundary layer induced by loop vortex filaments", Ph.D., June 1987.

Theses in Progress
(expected completion date in parentheses)

1. Peridier, V., "Strong interactions in turbulent boundary layers", Ph.D. thesis (June 1988).

2. Lu, L.J., "Determination of turbulent flow structure using pattern recognition of hairpin vortices", Ph.D. thesis (January 1988).

3. Haidari, A.H., "The three-dimensional flow field of single hairpin vortices", Ph.D. thesis (June 1988).

4. Taylor, B.K., "The effect of pressure gradients on the generation, development, and interaction of hairpin vortices", Ph.D. thesis (June 1988).

5. U. Sobrun, "Evolution and effects of hairpin vortex motion", Ph.D. thesis (June 1990).

5. PERSONNEL

A. Co-Principal Investigators

C.R. Smith, Professor of Mechanical Engineering
J.D.A. Walker, Professor of Mechanical Engineering

B. Research Associates

S. Hertzog, Post-Doctoral Research Associate

C. Student Research Assistants

		(Comp. date)
V. Peridier	Ph.D. Candidate	June 1988
L.J. Lu	Ph.D. Candidate	January 1988
A.H. Haidari	Ph.D. Candidate	June 1988
B.K. Taylor	Ph.D. Candidate	June 1988
U. Sobrun	Ph.D. Candidate	June 1990

END
DATE
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